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Thursday, October 16, 2014

Transportation, divergence, and the industrial revolution

After about 1000 AD northwestern Europe started a gradual switch from using oxen to using horses for farm traction and transportation. This trend culminated in an eighteenth-century explosion in roads carrying horse-drawn carriages and wagons, as well as in canals, and works greatly extending the navigability of rivers, both carrying horse-drawn barges. This reflected a great rise in the use of cultivated fodder, a hallmark of the novel agricultural system that was evolving in northwestern Europe from the start of the second millennium: stationary pastoralism. During the same period, and especially in the seventeenth through nineteenth centuries, most of civilized East Asia, and in particular Chinese civilization along its coast, navigable rivers, and canals, faced increasing Malthusian pressures and evolved in the opposite direction: from oxen towards far more costly and limited human porters. Through the early middle ages China had been far ahead, in terms of division of labor and technology, of the roving bandits of northern Europe, but after the latter region's transition to stationary pastoralism that gap closed and Europe surged ahead, a growth divergence that culminated in the industrial revolution. In the eighteenth century Europe, and thus in the early industrial revolution, muscle power was the engine of land transportation, and hay was its gasoline.

Metcalfe's Law states that a value of a network is proportional to the square of the number of its nodes. In an area where good soils, mines, and forests are randomly distributed, the number of nodes valuable to an industrial economy is proportional to the area encompassed. The number of such nodes that can be economically accessed is an inverse square of the cost per mile of transportation. Combine this with Metcalfe's Law and we reach a dramatic but solid mathematical conclusion: the potential value of a land transportation network is the inverse fourth power of the cost of that transportation. A reduction in transportation costs in a trade network by a factor of two increases the potential value of that network by a factor of sixteen. While a power of exactly 4.0 will usually be too high, due to redundancies, this does show how the cost of transportation can have a radical nonlinear impact on the value of the trade networks it enables. This formalizes Adam Smith's observations: the division of labor (and thus value of an economy) increases with the extent of the market, and the extent of the market is heavily influenced by transportation costs (as he extensively discussed in his *Wealth of Nations*).

The early industrial revolution was highly dependent on bringing together bulk goods such as coal and iron ore. Land transportation of such materials more than a dozen miles in most parts of the world was prohibitively costly, and they were only rarely located a shorter distance from navigable water (the costs per mile of water transport were generally orders of magnitude cheaper than the costs per mile of of land transport). As a result, the early industrial revolution, and the potential for a region to be the first to industrialize, was very sensitive to small changes in land transportation costs.

Furthermore, land and sea-borne transportation were far more complements than substitutes. Cheaper land transportation was a

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Nick Szabo

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"force multiplier" for water transportation. Decreasing the costs of getting to port from field or mine by a factor of two increased the number of fields and mines accessible by a factor of four, and increased the number of possible ways to divide labor, and thus the value, by an even greater factor via Metcalfe's law. This in turn incentived greater investment in sea-borne transport. It's thus not surprising that, even before the industrial revolution, the leaders in global trade and colonization were European countries that could access the Atlantic.

By the dawn of the industrial revolution in northwest Europe the effects of horse haulage had already been dramatic: drop by a factor of two in the costs, and increase in speed by about the same factor, of transporting goods by land, the corresponding increase in commercial crop area and in area that could be economically lumbered and coal and metals that could be mined. Multiply that factor of four by much more when we factor in (1) innovations in wheels, tires, shock absorption, and road building that followed on the heels, as is were, of the great increase in horse haulage, and (2) the great increase in mileage and inland penetration of navigable rivers and canals, especially in the 18th century, the barges again hauled by horses. And as Metcalfe's Law suggests, the number of combinations, and thus the value, increased by a far greater factor still. Not only did northwestern European ports have access to far more land, but there were far more ports far more "inland" along rivers and canals, thanks again chiefly to the draft horses and the nutrient-rich cultivated fodder that fed them.

To enable the industrial revolution, mines and nutrient-dense fodder had to be colocated within efficient bulk transport distance of each other — which in the case of horses hauling coal or wood by rural road, was typically less than twenty miles, and for oxen and human porters far less still — to produce the low-cost bulk transportation networks needed to make industrial revolution scale use of most commercial crops and mines. Efficient bulk transportation is needed _all the way_ between the iron mine, the coal mine, and the smelter. Because the cost per mile of water transport was so much smaller than the costs of land transport, this “last few miles to the mine” problem usually played a dominant role in transportation economics, somewhat analogous to the “last mile” problem in modern cable networks. That’s why stationary pastoralism with its efficient markets for nutrient-dense (because cultivated) fodder was such a huge win — it allowed horses to be housed at the mines, canals, roads, and factories where they worked, which no place in the world outside Europe could during that era do. Nutrient-dense fodder created a virtuous recursion, enabling itself to be harvested (via horse-drawn mows and rakes) and transported to mine, factory, and stable at increasingly lower costs.

Industrialization came in many phases. Very roughly speaking, the first phase, in the latter half of the eighteenth century, involved the culmination and optimization of the use of horses, by northwestern Europe, and especially England, greatly expanding its horse wagon and carriage roads and horse-drawn barge canal networks. Horses brought coke or charcoal and iron ore to the smelters. Horse-powered capstans performed some arduous farm tasks such as threshing. Along with primitive Newcomen steam engines they pumped coal mines. Horse gins also powered most of the early versions of innovative textile machinery (they switched to more power-efficient water mills when they later scaled up). That classic carnival ride, the merry-go-round, was inspired by these perpetually circling horses.

Again roughly speaking, the second phase of industrial growth, after about 1830, was more scientific and far easier to copy than northwestern Europe's unique biology: steam engines came to replace horse gins and water mills for running industrial machinery, and the steam-powered railroad radically lowered transportation costs between major mines, factories, and urban centers. When non-European countries industrialized, such as Japan after the 1870s, they did it in a "leap-frog" style: they skipped over the long-evolved improvement in draft animals and went straight to mature steam engines and, soon thereafter, electrical motors. Much as countries installing phone networks for the first time over the last few decades have leap-frogged over the land line era, going straight to cell phones. Starting early in the 20th century industrializing countries could replace all the remaining important functions of the horse with internal combustion engines. England, which made the longest and most thorough use of the horse, and thereby had the transportation economies allowing it to pioneer the industrial revolution, had a less pressing need to use the internal combustion engine and thus lagged enough in that technology so that second-generation industrializers like Japan, Germany, and the United States became leaders in internal combustion engine products.

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Given the scientific nature of the second phase of the industrial revolution, which could be discovered by any culture full of literate craftsmen, this second phase was more technologically inevitable and didn't ultimately depend on northwestern Europe's unique biology. At the same time, during the long evolution that culminate in the industrial revolution, and during its first phase, land transportation the world over was muscle powered and the unique system of stationary pastoralism, by breeding draft horses that ran on cultivated, nutrient-dense fodder, substantially lowered transportation costs. This allowed the value of northwestern Europe's bulk transportation networks to radically increase and made it very nearly as inevitable that that region would be the pioneers of the industrial revolution.

Hat tips and references: Edward Wright and Raymond Crotty among many other authors have explored some of these issues.

Posted by Nick Szabo at 2:00 PM

10 comments:

moa said...

Side note: Oats and barley grains are staples for horses. Ease of transportation of sacks of high-energy density grains for the horses would be a significant multiplier in economic distance (and season) from harvest also.

4:50 PM

Jeff McDonald said...

Good post. The Twitter feed is nice, but sometimes it is good to hear a longer and more in depth explanation of something. I am so hungry for thoughts like this one.

2:03 AM

Anonymous said...

This quote might be of interest:

"The technologies which have had the most profound effects on human life are usually simple. A good example of a simple technology with profound historical consequences is hay. Nobody knows who invented hay, the idea of cutting grass in the autumn and storing it in large enough quantities to keep horses and cows alive through the winter. All we know is that the technology of hay was unknown to the Roman Empire but was known to every village of medieval Europe. Like many other crucially important technologies, hay emerged anonymously during the so-called Dark Ages. According to the Hay Theory of History, the invention of hay was the decisive event which moved the center of gravity of urban civilization from the Mediterranean basin to Northern and Western Europe. The Roman Empire did not need hay because in a Mediterranean climate the grass grows well enough in winter for animals to graze. North of the Alps, great cities dependent on horses and oxen for motive power could not exist without hay. So it was hay that allowed populations to grow and civilizations to flourish among the forests of Northern Europe. Hay moved the greatness of Rome to Paris and London, and later to Berlin and Moscow and New York."

Freeman Dyson

6:49 AM

nick said...

moa: I suppose "multiplier" is a more traditional way to say "virtuous recursion." :-) Cultivated oats and barley were indeed staples for horses as well as peasants. Two different solutions to the Malthusian dilemma: China used their humans as draft animals, whereas the English used horses and might feed them in preference to feeding the humans. Even as late as the 1840s complaints were heard that the English "fed their horses before they fed the Irish".

Jeff, thanks.

Anonymous, great observation and insight from that neglected genius.

Here's a great map showing the very widespread and local nature of the English canal system, which greatly increased the area within short land transport distance of the far cheaper water transport (both horse-powered):
http://en.wikipedia.org/wiki/File:Map_of_canals_of_the_United_Kingdom.png

5:04 PM

nick said...

Notice the resemblance of the British canal networks to the veins in leaves or an animal circulatory system. Within geographical constraints, this canal network is close to an optimal space-filling flow network, reaching within short land distance transport to nearly the entire area, O(n^2). A good highway/road/street network is similar.

6:37 PM

moa said...

nick:

thanks for the canal network note. There maybe some mileage to be had in looking at fractality of such network structures. Also, it has just triggered a new thought on a long held notion/problem I've been pondering for fluid dynamic turbulence, (vortex cascades) and fractal networks (self-similar or scale-free) in general. Particularly your comment about "optimal ... networks".

9:10 PM

Jonathan R. said...

"Notice the resemblance of the British canal networks to the veins in leaves or an animal circulatory system"

FYI, that pattern you are describing is called dendritic.

Love your thoughts and i am impatiently looking forward to a renewable powered, electrical and bitcoin enabled economy.

7:14 PM

Harold said...

Nick, have you read Lucio Russo's book? As one of his contentions is that more than an elite with a scientific mindset is needed to kick off a scientific-industrial revolution I have been reading some of your writings. But I would be interested to know, if you have read his book, if you thought his main premise to be correct.

2:19 AM

Sarah Smith said...

FYI, that pattern you are describing is called dendritic.

Love your thoughts by the way. thanks for share..

Transportation

9:17 PM

Anonymous said...

Don't overlook the origin of the merry-go-round in the late medieval game of "carousel" (e.g., https://en.wikipedia.org/wiki/Carousel), a less-violent replacement of jousting.

10:41 PM

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